

Proton Beam Formation at Fermilab for $\mu 2e$ (and for NF/MC)

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Abstract. Proton bunch formation from the Fermilab proton sources for the $\mu 2e$ experiment is discussed. In the initial scenario a single intense $h=1$ bunch is formed in the Accumulator/Debuncher, with slow extraction providing the required spill. However, the $\mu 2e$ experiment could use $h=4$ bunching in the Accumulator rather than $h=1$, with the 4 bunches fed one at a time into the more isochronous Debuncher for slow extraction. The $h=4$ variant has several advantages and a few disadvantages, and can reduce peak beam intensities, and therefore improve space charge limits. The method can be extended to project X to enable high duty cycle extraction within space charge limits. A further extension should make possible an accumulator/buncher scenario that can provide 8 GeV short bunches for a neutrino factory and/or muon collider scenario.

Keywords: muon, muon conversion, proton source, muon collider, neutrino factory

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INTRODUCTION

The $\mu 2e$ collaboration has proposed a muon conversion experiment at Fermilab[1], where that experiment follows the design presented in the MECO proposal, accepted but not implemented at BNL[2]. The experiment requires ~ 8 GeV protons, with the proton beam reaching the experimental target in relatively short clumps of beam (~ 100 ns), followed by gaps of $\sim 1.5 \mu$ s, where no beam is received (at $< 10^{-9}$ extinction). π 's are produced in the target and μ 's from the π decays are captured in the atoms of a secondary target and the decays of captured μ 's within the 1.5μ s window are searched for evidence of $\mu \rightarrow e$ conversion. Any events would demonstrate new physics.

In the $\mu 2e$ proposal the proton beam is obtained by slow extraction from a ~ 100 ns long bunch circulating in the $\sim 1.6 \mu$ s circumference Fermilab Debuncher ring. In this note we describe the bunch formation presented in the $\mu 2e$ proposal, and then describe a variant scenario that uses the Accumulator to form multiple bunches that are then transferred one at a time into the Debuncher for slow extraction.

The variant is more naturally extendable to handle the higher intensities possible with a Fermilab injector upgrade, and can be extended to obtain the short intense bunches (< 3 ns) needed for a neutrino factory or muon collider.

BASELINE SCENARIO

In the $\mu 2e$ proposal[1], a scenario for storing and extracting 8 GeV proton beam for the experiment was presented. In that initial scenario, several Booster cycles of proton beam are transported into the Fermilab Accumulator, where they are adiabatically debunched and stacked in momentum space, following a stacking scenario developed by McGinnis[3]. That stacking procedure could take from 1 to 6 batches from the Booster.

In this initial "McGinnis" stacking, the proton beam is transported from the Booster as a single-turn batch of ~ 80 53 MHz bunches. In the present scenario, that transport goes from the Booster through the Recycler and the AP0 line into the Accumulator, rather than through a newly constructed injection line. That batch is captured in 53 MHz rf in the Accumulator where it is decelerated and debunched into a stacking orbit as a single-turn bunch with a longitudinal phase space of ~ 8 eV-s. The stacking/debunching cycle takes only ~ 16 ms, a fraction of the 67 ms Booster cycle time. The stacking can continue for up to 6 batches, adding $\sim 4 \times 10^{12}$ protons within ~ 8 eV-s to the Accumulator beam with each batch. Initial scenarios would take only ~ 2 to 4 batches, to avoid intensity limitations.

This proton beam is then adiabatically formed into a single bunch in the Accumulator using an $h=1$ rf

system with relatively weak voltage. That bunch is transferred into the Fermilab Debuncher where it is compressed to a short bunch (~ 40 ns rms) by $h=1$ bunch rotation (~ 40 kV) and held in that short bunch configuration (using ~ 200 kV of $h=4$ rf) while slow-extraction removes the beam from the ring. This scenario uses the less isochronous Accumulator ($\gamma_t = 5.5$) for the adiabatic bunch formation, and the more isochronous Debuncher ($\gamma_t=7.5$) minimizes the rf voltage needed for rotation into a short bunch and holding the bunch length for extraction [4].

Combining several Booster batches into a single bunch in the Debuncher implies relatively large space charge forces. An estimate of space charge effects can be found from the formula:

$$\delta v \cong \frac{r_p N}{4\pi\beta\gamma^2 B_F \epsilon_{N,rms}}$$

With the bunching factor $B_F = 0.06$ (100ns/1.7 μ s), and $N = 1.2 \times 10^{13}$ (~ 3 batches), $\epsilon_{Fermi} = 6\pi\epsilon_{N,rms} = 25\pi$ mm-mr, we obtain $\delta v \cong 0.065$, and the large space charge tune shift may make slow extraction difficult. ($\delta v < \sim 0.025$ would be preferred, but $\delta v \cong 0.05$ may be workable.)

This baseline scenario does minimize the number of ring to ring transfers and the resulting kicker requirements, and uses Accumulator/Debuncher properties to reduce rf requirements.

This scenario does have some disadvantages:

- Adiabatic $h=1$ bunching in the Accumulator is relatively slow. To avoid phase-space dilution, it requires ~ 0.2 s, and during that time the Accumulator cannot stack additional proton cycles.
- The compressed bunch is not that short. The large phase-space of the stacked booster cycles and the need to control space charge makes the rms bunch length ~ 40 ns (5σ fullwidth is 200ns), and that would make the extracted beam pulses longer than really desired.
- Even at $\sigma = 40$ ns, the space charge is relatively large and may prevent effective slow extraction.
- In part because of the space charge problem, it is not clear how a new proton driver could be used as a substitute for the Booster to provide more beam.

H=4 VARIANT

We present another scenario in which we initially stack proton beam in the Accumulator (much as before), but we then adiabatically bunch at $h=4$ in the Accumulator. We then transfer single bunches of these protons into the Debuncher, compress the bunch length and slow extract these single bunches.

This $h=4$ scenario has several advantages:

- Adiabatic $h=4$ bunching is much faster, and can be done in a fraction of a Booster cycle of 67ms. (30ms is very adiabatic.) $h=4$ bunching in 16ms is also possible but is not quite adiabatic and shows some phase space dilution.
- The beam transfers into the Debuncher require a fast kicker with ~ 100 ns rise time, ~ 200 ns flat top, ~ 100 ns fall time. These are relatively modest requirements. The transfer enables an additional step of extinction; beam is excluded outside the transfer window.
- The transfers into the Debuncher can rather naturally enable further bunch compression, and it is fairly easy to get $\sigma < 20$ ns. ($5\sigma < 100$ ns) (The match could also be tuned to keep a 40ns σ bunch length.)
- The space charge effect is reduced by the number of bunches (4), but is increased due to the shorter bunch length.

An initial simulation with adiabatic $h=4$ capture in the Accumulator and ~ 20 ns matched $h=4$ bunching in the Debuncher uses 25 kV of $h=4$ rf in the Accumulator and 300kV of $h=4$ rf in the Debuncher, and obtained very good behavior in longitudinal beam dynamics (see Fig. 1).

The major disadvantage of this $h=4$ scenario is that the Accumulator cannot be simultaneously used to accumulate booster batches while slow extraction is proceeding in the Debuncher. Instead, bunches are held in the Accumulator and fed one at a time into the Debuncher in the extraction cycle. (However, one could imagine box-car stacking several booster batches in the Recycler while slow extracting and then transferring these (batch by batch) to the Accumulator after the last transfer into the Debuncher [5]. With this addition of the Recycler as a holding ring, there is no loss of duty cycle, and it may be possible to extend the scenario to use all Booster batches.)

EXTENSION TO PROJECT X

The value of prebunching in the Accumulator ($h=4$ or 8 or ...) is probably enhanced when considering intensity increases using a "Project X" proton driver. Some very natural scenarios are suggested.

With Project X the full linac pulse could be injected into the Recycler, chopped to form 6 Accumulator length batches (with one accumulator length reserved as an abort gap, see Fig. 2.). These batches are transferred one by one into the Accumulator where they are adiabatically stacked in momentum space as in the initial McGinnis stacking scenario. (Weak 53 MHz rf systems in the Recycler and Accumulator could be used to manipulate the

beams for these scenarios.) The beam is then debunched to form a single long Accumulator length bunch which can be formed into $h=4$ bunches (or $h=?$) as in the scenario discussed above and displayed in Figure 1. These Accumulator bunches would then be transferred one by one into the Debuncher for further bunch rotation, and slow extraction. Figure 3 shows an overview of the Linac, Recycler, Accumulator and Debuncher cycle for an implementation taking one Linac pulse every 1.4s and feeding that beam from Recycler to Accumulator to Debuncher, obtaining continuous beam for mu2e. Note that a Linac pulse spacing as small as 0.4s would fit easily in the cycle.

With this extended scenario an entire Linac pulse (which may be 5 to 15×10^{13} protons) could be fed into the mu2e system without excessive space charge. (We do not yet know the space charge limit for an $h=4$ scenario, however. The larger pulse intensities would probably need $h=8$ or 12 or ...) The scenario would have close to 100% duty cycle.

EXTENSION TO FUTURE PROJECTS: ν -FACTORY AND $\mu^+ \mu^-$ COLLIDER

This method could be modified to obtain very short bunches for future applications; that is to obtain very short intense bunches for the front end of a ν -factory or μ collider (NF/MC). The Recycler is not used and the 8 GeV Linac beam is injected into a new "Accumulator" much like the Accumulator. The injected beam would have the minimal momentum spread of the linac beam after injection line phase rotation ($\Delta E = \pm 2 \text{ MeV}$ full width) so that the initial longitudinal emittance is as small as the energy width times the ring circumference ($\sim 300 \text{ m}$). This beam is then adiabatically bunched in $\sim 0.05 \text{ s}$ in a low-voltage ($< 5 \text{ kV}$) rf system at $h=4$ (or more). Then single bunches (or all four) are transferred into a Buncher ring of the same circumference, where a $\sim 100 \text{ kV}$ rf system ($h=4$) rotates them in a $1/4$ synchrotron period to a short bunch ($\sim 1 \text{ m}$ rms or less), which would then be extracted onto a target. The parameters obtained in a simple AccumulatorDebuncher-like system are very close to what is needed for a neutrino factory or muon collider system. Fig. 4 shows a simulation at Accumulator/Debuncher parameters. (obtaining $\sim 1.5 \text{ m}$ rms)

In a redesigned scenario optimized for the NF/MC, the Accumulator/Debuncher would have a larger aperture and a smaller circumference, would perhaps produce 6 bunches, and be able to obtain shorter bunches than this initial extrapolation. Future studies toward studying this model toward an optimum NF/MC implementation have been initiated [6].

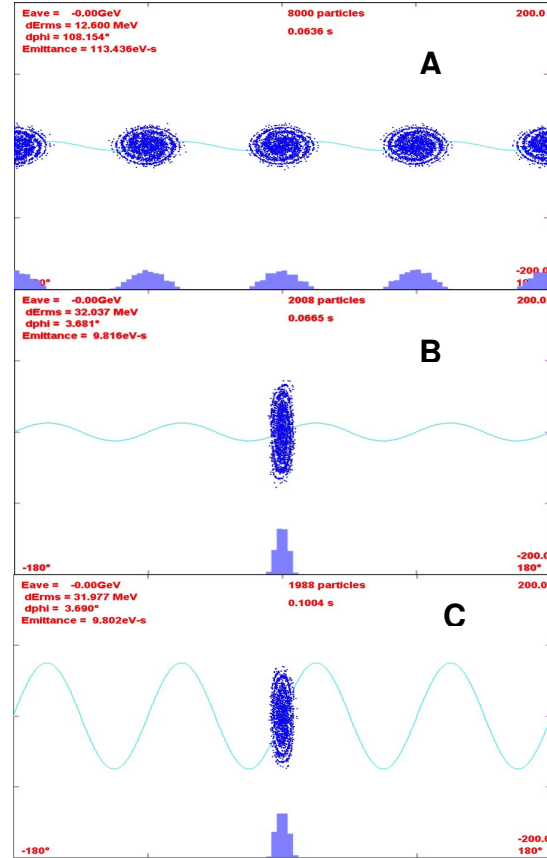


Figure 1. $h=4$ Simulation of longitudinal motion. In this simulation protons are adiabatically bunched into 4 bunches in the Accumulator(A). A single bunch is transferred into the Debuncher where it is rotated to a short bunch ($\sigma=18 \text{ ns}$) (B). An rf voltage keeps the bunch fixed at that length through extraction (C). In each of these graphs the x-coordinate is phase around the ring (-180° to $+180^\circ$), and the y coordinate is the energy offset δE (-200 to $+200 \text{ MeV}$)

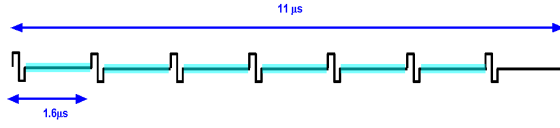


Figure 2: Filling pattern from Project X into the Recycler. The linac beam is chopped to form 6 Accumulator-length batches, as the linac beam fills the Recycler over ~ 1 ms (100 turns) or a full Project X pulse. The batches are transferred one by one into the accumulator where they are adiabatically stacked in momentum space as in the initial McGinnis stacking scenario.[3] The beam is then debunched to form a single long accumulator length bunch which can be formed into $h=4$ (or more) bunches as in the scenario displayed in figure 1. These bunches are then transferred one by one into the Debuncher for further bunch rotation and subsequent slow extraction.

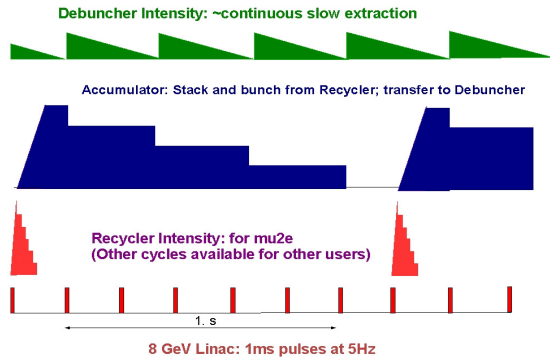


Figure 3. Cartoon representation of mu2e cycle with an 8 GeV linac pulsing at 5 Hz, and mu2e taking one of seven pulses. A single pulse is captured in the Recycler, where 6 batches are transferred into the Accumulator for McGinnis stacking (0.1s). The beam is adiabatically bunched (~ 0.07 s) into $h=4$ bunches which are transferred 1 by 1 into the Debuncher for slow extraction. The resulting extraction is nearly DC. Note that more than 1 of 7 linac pulses can be used if desired and if available, and h can also be increased if needed.

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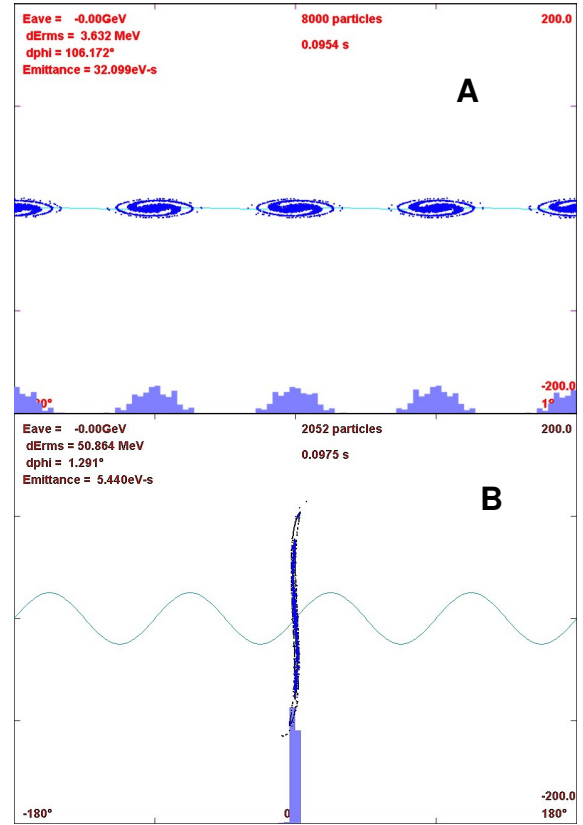


Figure 4: Bonus Application. For a neutrino factory/ muon collider scenario, one would inject a full linac pulse into the circumference of a new buncher ring or “Accumulator”. The Accumulator would adiabatically bunch this into 4 bunches (A). After this, single bunches (or all 4) are transferred into a “Buncher” where the bunches undergo $1/4$ oscillation to short bunch length (B).

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